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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFGL-TR-82-0340	2. GOVT ACCESSION NO. AD-A121942	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Speckle Interferometry I: A Test on an Earth Orbital Satellite		5. TYPE OF REPORT & PERIOD COVERED REPRINT
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Simon P. Worden, Capt, USAF N. J. Woolf* E.K. Hege* P. A. Strittmatter* E. N. Hubbard*		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Geophysics Laboratory (PHS) Hanscom AFB Massachusetts 01731		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2311G317
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory (PHS) Hanscom AFB Massachusetts 01731		12. REPORT DATE 18 November 1982
		13. NUMBER OF PAGES 25
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES
*Steward Observatory, The University of Arizona
Reprinted from AFSC Space Division (SD-TR-82-46), 15 April 1981, Final Report,
pp 1-22

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Speckle interferometry
Image reconstruction

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The astronomical technique known as speckle interferometry shows considerable promise for satellite surveillance and imaging. With speckle interferometry, it is possible to remove image degradation caused by atmospheric turbulence. In this way, resolution on satellite images could be improved by a factor of fifty with existing telescopes. We used this method to determine the size and shape of a high altitude satellite. Without speckle interferometry, such information would be impossible to measure. However, to produce routine satellite images we are developing improved computer processing. Even with speckle interferometry we can only marginally

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resolve high altitude satellites. To provide satisfactory imagery of these objects we need telescopes much larger than existing instruments. To this end we are working to adapt a large multiple mirror telescope system for speckle interferometry. This telescope is the prototype for telescopes, a factor of ten larger than any now existing.

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FOR THE COMMANDER

Thomas W. Flattery, COL, USAF
Program Manager
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SUMMARY

Turbulence in the Earth's atmosphere causes "seeing" which badly degrades images of objects outside the atmosphere. The technique known as speckle interferometry has shown considerable promise for recovering the information lost to this degradation. We have developed a television detector to record the short exposure data needed as input for speckle interferometry, and we have perfected computer methods to process this data. We have performed a test of our system on a satellite test target, successfully measuring the known size and shape of the object. Yet we still need to improve our ability to track satellite targets so we can observe larger, more interesting objects and demonstrate a complete image reconstruction. Finally, we have pointed out that telescopes larger than any existing are needed to obtain useful resolution on high-orbit objects. The new Multiple Mirror Telescope in Tucson, AZ will prove to be important in showing that a telescope as large as 25 meters can be built and will work to reconstruct images appropriate to its full 25 meter size.

CONTENTS

TABLES

FIGURES

I. INTRODUCTION

"Seeing," caused by turbulence in the Earth's atmosphere, degrades images from ground-based telescopes to 1 arc-second resolution (about the size of a dime seen at one mile). Without this degradation, the resolution obtainable, which is said to be "diffraction limited," is inversely proportional to the telescope diameter. For the largest existing ground based telescopes ($\approx$ 5 meter diameter), potential resolution is about 0.021 arc-second, a factor of 50 increase over the seeing limit. To put this in scale, we present in Table 1 the linear size of seeing and diffraction limited images for a variety of telescopes and satellite ranges. Clearly, much could be gained by devising means to achieve the full resolving power of ground-based imaging systems.

Table 1. Telescope Resolution Capabilities

Distance (km)	Atmospheric Limit 1 arc-sec	4-meter Limit 0.028 arc sec	25-meter Limit 0.004 arc sec
150	72 cm	2 cm	0.2 cm
1000	5 m	13 cm	2 cm
10,000	50 m	1.3 m	20 cm
40,000 (sync orbit)	200 m	5 m	80 cm
1.5×10^8 (sun)	700 km	20 km	3 km
670 kpc (M31)	3.1 pc	0.089 pc	0.013 pc

Astronomers have struggled for centuries with the desire to improve imaging. Choosing the best sites and designing telescopes to minimize susceptibility to turbulence can improve images by up to a factor of two. In the

5

1920's, A. Michelson showed that interferometry could be used to achieve the full theoretical resolution on astronomical objects. However, until 1970, the hope of obtaining the full resolving power of a large optical telescope seemed out of reach. In 1970, A. Labeyrie, a French astronomer, proposed using very short exposure photographs, in a form of interferometry which he called "speckle interferometry," to realize the full capabilities of existing ground-based telescopes. In 1972, Gezari, et al., demonstrated that sizes and shapes (but not actual images) could be determined down to the 5 meter (200 inch) Palomar telescope diffraction limit of 0.021 arc-seconds. In 1975 Lynds, et al. showed that speckle interferometry could be adapted to produce actual images down to the 0.028 arc-second limit of the Kitt Peak National Observatory 4 meter (158 inch) telescope for bright stars.

In view of its possible relevance to satellite identification and surveillance, the Air Force Geophysics Laboratory began a program to apply speckle interferometry to satellites. It was necessary to develop two areas. Because satellites are much fainter than the brightest stars, instrumentation to observe faint objects was developed. In addition, the data reduction methods were not usable for general-purpose image reconstruction. We have now solved both of these problems. In this report we provide a non-technical description of the system and a demonstration of its use for studying an orbital satellite, a Soviet Molniya communications satellite. We also provide a brief discussion of the need for larger telescopes. In paper II we provide a detailed technical tutorial of current methods and status of speckle interferometry.

II. HOW SPECKLE INTERFEROMETRY WORKS

Before we continue, it is necessary to review the basic features of
Fourier Mathematics which are essential in any discussion of optical systems.
An image is generally represented as a set of light intensities as a function
of the "real" coordinates x and y. This image may equally well be represented
as a set of harmonic frequencies, usually sines and cosines. In Figure 1 we
show this graphically. Assume a real function $f(x) = 2x \sin(6\pi x)$, which is a
simple sine curve showing three cycles between zero and one with an amplitude
of 2. The Fourier representation, or transform, of this function has zeros at
all points except at a frequency of 3 where ($2\pi f = 6\pi$) the value would equal
2, the amplitude of our sine curve. Yet, there is an ambiguity in this
representation. Suppose we added a constant in the sine term with $f(x) = 2x$
$\sin(6\pi x + 1.57)$. This function has the same frequency representation as the
original one, yet it is shifted relative to it. To represent this in the
Fourier transform, each frequency has an amplitude as described above, and a
phase which represents the shift; in this case $1.57 = \pi/2 = 90°$, so the phase
is $\pi/2$ or $90°$. Since phase is a circular function, it repeats at multiples of
2π. That is, a phase of 3π is the same as a phase of π etc.

All images may be represented by their Fourier Transforms. Most optical
systems act as a form of analog Fourier Transform device, thus the usefulness
of Fourier analysis. Generally the amplitude is far easier to measure, in the
form of a power spectrum, and the phase is lost. However, for reconstruction
of images from Fourier Transforms, phase information is vitally important and
must be recovered by some means. It is intuitive that a large object is re-
presented by predominantly low frequencies and a small item by high frequen-
cies. Thus, large objects tend to be "small" in their Fourier transforms and
vice versa.

At the image plane of a telescope we measure the Fourier amplitude of the
light waves entering the telescope aperture. In Figure 2 we show this process
schematically. Light waves from a distant star enter the telescope in Figure 2a
in a form known as a plane wave, which is very much like an ocean wave with

the wave amplitude and the location of wave peaks and troughs the same across the whole aperture. In other words, the phase of the incoming wave is constant. The resulting image is said to be "diffraction limited." Since the image is the Fourier amplitude of the incoming wave, it is easy to see that a larger aperture telescope should produce a smaller (i.e., better resolution) image. However, one gets perfect plane waves only in a laboratory or above the Earth's atmosphere. In practice, light waves passing through the Earth's atmosphere are broken both in phase and amplitude into small segments of varying extent averaging about 10 cm in size as shown in Figure 2b. Moreover, this breakup process changes very rapidly; significant changes occur in less than 1/20 sec under typical conditions. The resulting image, as the Fourier transform of this function, contains mostly low frequencies which carry primarily information about the breakup process. The image is spread out considerably although it still contains some high-frequency, high-resolution detail. Conventional telescope photos have long exposures compared to the atmospheric change time and this remaining high-frequency, high-resolution detail is washed out. What is left is an average image with one-arc"second resolution typical of a 10 cm telescope. Images are no better for even the largest telescopes. This image degrading process is called "seeing" by astronomers.

In 1970, A. Labeyrie pointed out that the small amplitude, high-frequency information at the telescopes' full resolving power could be recovered from exposure photos which were shorter than the atmospheric change time. In these short exposure photos, atmospheric turbulence is "frozen" and the telescope behaves like the "multiple aperture interferometer" shown in Figure 2c. Some of the small patches distributed over the telescope aperture will be in phase at a given instant. Those in phase act in concert to produce a telescope diffraction-limited image, but since many groups of such concordant patches exist and have different phases, a large set of such images is produced with each one shifted relative to another. Short-exposure star photos in Figure 3 show this "speckled" effect. The individual dots may approach perfect telescope images: for the binary star in Figure 3c they are double, and for the large star in Figure 3a they are larger than for the unresolved star in 3b.

This fact was used in 1975 by R. Lynds, S. Worden and J. Harvey at the Kitt Peak National Observatory to put together the first image of the surface of another star, the supergiant star Betelgeuse. The resemblence of these photos to laser speckle photos has led to the process being called "speckle interferometry." For complicated objects like near-Earth-orbit satellites, the speckles overlap and single images are impossible to disentangle. For faint objects like high-orbit satellites, only a few photons are detectable and individual speckles are not well-enough defined to be picked out. Labeyrie developed a method to process this data to produce the Fourier amplitude of the image. From such data, size and shapes could be determined, but not actual images. For that, the Fourier phase is required as well. Labeyrie's method was also difficult to calibrate to produce good quantitative results. Our group, including the authors of this paper, has developed a method to calibrate Labeyrie's Fourier analyses to get accurate sizes and shapes.

In 1978, at the Environmental Research Institute of Michigan, J. Fienup developed a method to obtain the Fourier phase from an iterative mathematical computer method using only the amplitude as an inupt. We have used this method with considerable promise to get diffraction limited images of simple objects like binary stars, and are now in the process of applying it to more complex objects.

III.   INSTRUMENT AND DATA

The photos shown in Figure 3 were obtained in a very simple manner and
they suffer from a number of drawbacks. A 35 mm camera was placed behind an
image intensifier to record the short exposure photos on film. Since the image
intensifier is slow to return to a ready condition, a shutter allows only
about 1 frame per second so that the intensifier will settle down between
shots. Since the actual exposure time is about 1/100 second, 99 percent of
the light is lost. Moreover, the resulting photographs suffer from a variety
of photographic non-uniformities and require a time-consuming process to digi-
tize for computer processing (up to 5 minutes per frame). For faint objects
with only a few photons per frame, at least 10,000 frames are needed to get a
usable result. With the photographic system outline above, this means over 3
hours observing time and 40 days data processing! To speed up this process,
we replaced the film with a television camera. The television records a frame
every 1/60 of a second. We run the camera without a shutter and the televi-
sion output is directly computer processed in a device known as an "array
processor." This unit compares each frame with previous ones and makes sure
we only record a new photon when it arrives. The Fourier analysis may also be
done at this time. With this system we can observe, record, and process data
to obtain our result at the telescope all in less than 5 minutes, to do what
previously would have taken months.

As a demonstration of our capabilities, we used our system on a Soviet
Molniya communications satellite shown in Figure 4. This object has a 12-hour
orbit, during which time it moves from an altitude of about 5000 km to a syn-
chronous distance of 40,000 km. With a size of about 5 m, at these altitudes
this object should be marginally resolvable with large existing telescopes
like the University of Arizona 90 inch (2.3 meter) instrument. Despite its
marginal suitability for study, we chose it since there are few objects large
enough and at a high enough orbit so that relatively slow astronomical tele-
scopes can track them. For further demonstrations we plan to use faster
telescopes and larger objects.

For our test, 15 minutes of data were obtained of the object on 7 July 1979 beginning at 0250 Greenwich Mean Time. The mean range of this target during the observation period was 21,500 km. We also obtained a similar amount of data on a point source (unresolved) star for comparison purposes. About 4×10^5 photons were detected for the target for about 15 photons per frame. We processed a sample of the data as described above to produce the Fourier amplitude (power spectrum) of both the target and the point source. Our results are displayed in Figure 5.

The results require some words of explanation. We did not try to recover the phase to produce an actual image of this object for two reasons. First, the object is only slightly larger than an unresolved object and it would not show much structure at our resolution. Second, the target spins once per second. The several-minute observation period averages the spinning, so that only the pattern of the spinning solar panels would be visible, much as the spinning blades of a helicopter. Since the target is locked on the sun and we observed it at an angle, we expect to see only the oblong pattern of the spinning panels. What we have displayed is the "autocorrelation" of the actual image. The autocorrelation is computed by inverse Fourier transforming only the _amplitude_ or power of the image's Fourier transform (ignoring the phase), but it can be better visualized by an analogy. A photo of an object is taken and a copy made of it; the original is then laid on top of the copy as shown in Figure 6. A light is shone through the two photos and the amount transmitted measured by a photocell. If we measure the change of this light level as we slide the copy in one direction relative to the original, we are measuring the autocorrelation along that direction. This function is very useful in studying the size and shape of an object. It follows that the autocorrelation of an oblong object would be oblong and that of a round object would fall to zero outside the diameter of the object. In this way, we can use the autocorrelation to measure the size and shape of the test target. Since the target is only slightly larger than the telescope resolution limit (see Figure 7), its autocorrelation is only slightly larger than the unresolved star. None-theless, the expected oblong shape is readily apparent. From this data we were able to derive a size of 4^{+2}_{-1} meters for the target, in excellent

12

agreement with its actual size of 4.9 meters. The uncertainty in the results
is set by our ability to remove the effects of the telescope itself, for which
we use the observations of the point-source star, and which in turn is limited
by the size of the telescope.

From these highly promising results, we see two directions for future
work. As mentioned previously, faster tracking is needed to observe lower
orbits and larger objects. High-rate tracking capability is available on
several existing telescopes, such as a 48-inch telescope in Cloudcroft, NM.
Using these telescopes we plan demonstrations of our method. Moreover, we
recognize that actual reconstructed images, rather than autocorrelations, are
essential. Based on our recent astronomical results, we are confident that
the Fienup computer method will give us the phase information we need to
completely recover images.

If we review Table 1, it is clear that the largest existing telescopes
($\sim$ 5 meters diameter) do not produce usable images for synchronous objects,
even with speckle interferometry. A much larger telescope is clearly re-
quired, perhaps near 25 meters in diameter. The University of Arizona, in
concert with the Center for Astrophysics in Cambridge, MA, has recently com-
pleted an instrument which may prove that a 25-meter telescope could be con-
structed. This telescope, shown in Figure 8, consists of six separate, 72-
inch mirrors, but it can be used for speckle interferometry like a single 7-
meter telescope. We are currently involved in projects to evaluate this
"Multiple Mirror telescope" for image reconstruction and to study what would
be entailed in scaling it up to 25 meters.
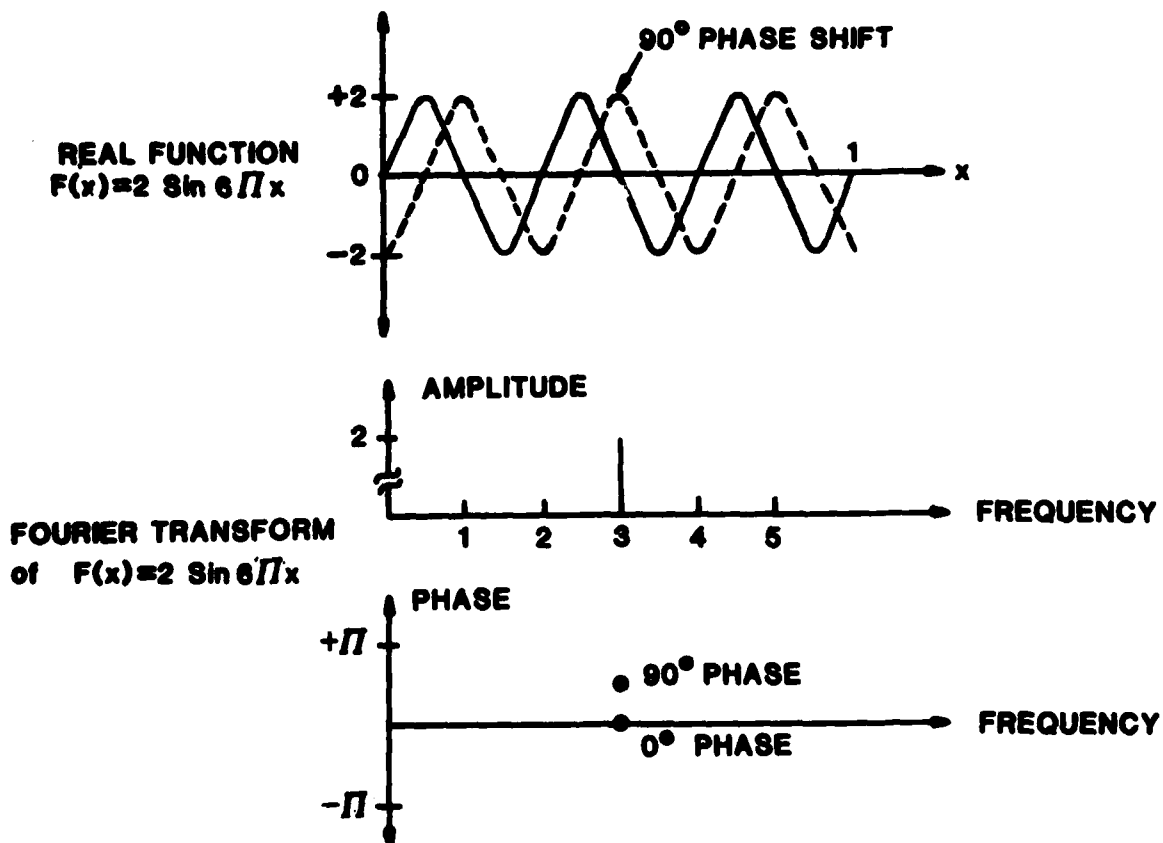
NOTE: A real function can be decomposed into a series of sines and cosines.

Figure 1. Schematic Representation of the Fourier Transform

15
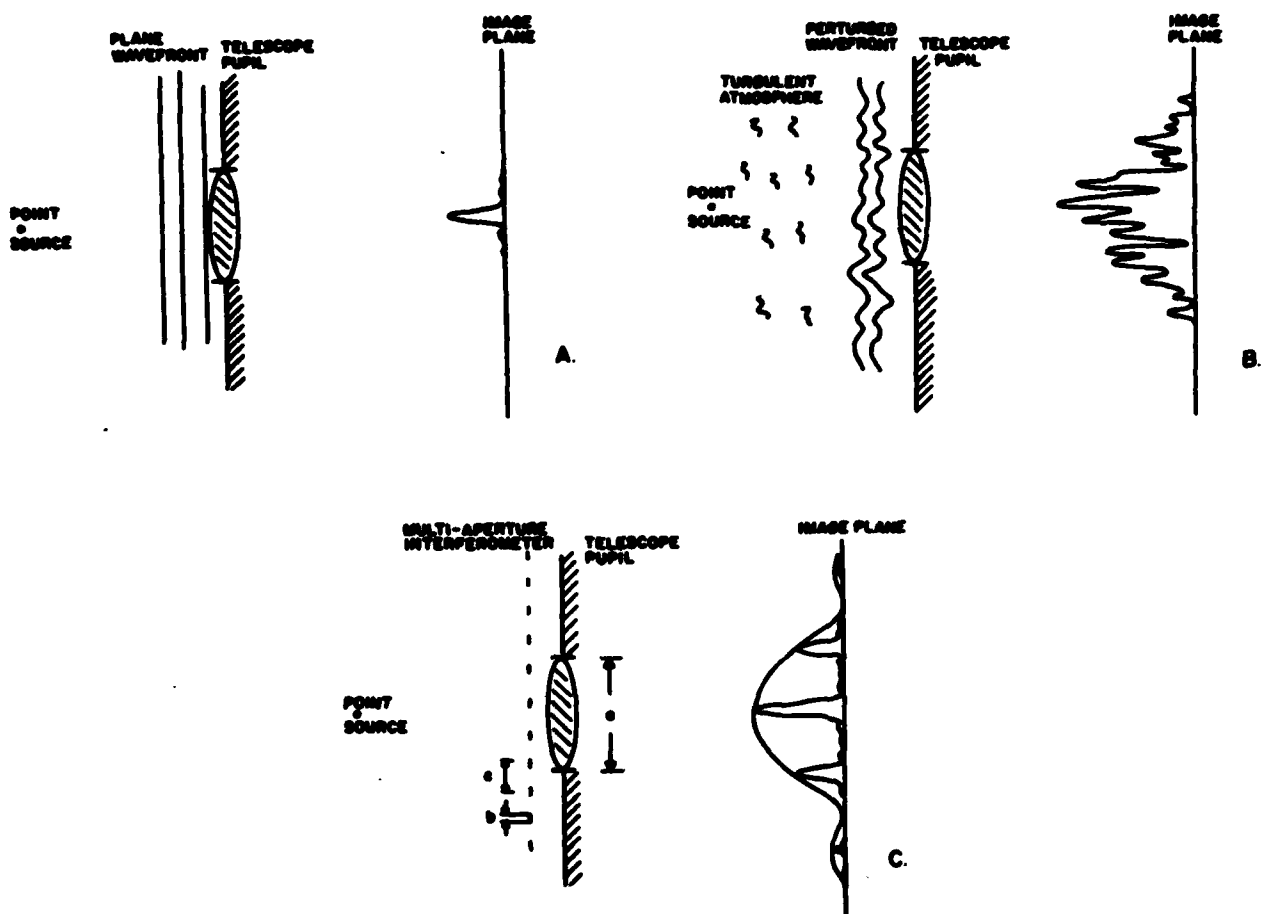
NOTE: In 2a, an ideal situation with an incoming plane wave from
a point source is shown. In 2b, the atmosphere has broken
the plane wave into 10 cm segments which may be modeled
instantaneously as a multiple aperture interferometer (2c).

Figure 2. The Image-Forming Process
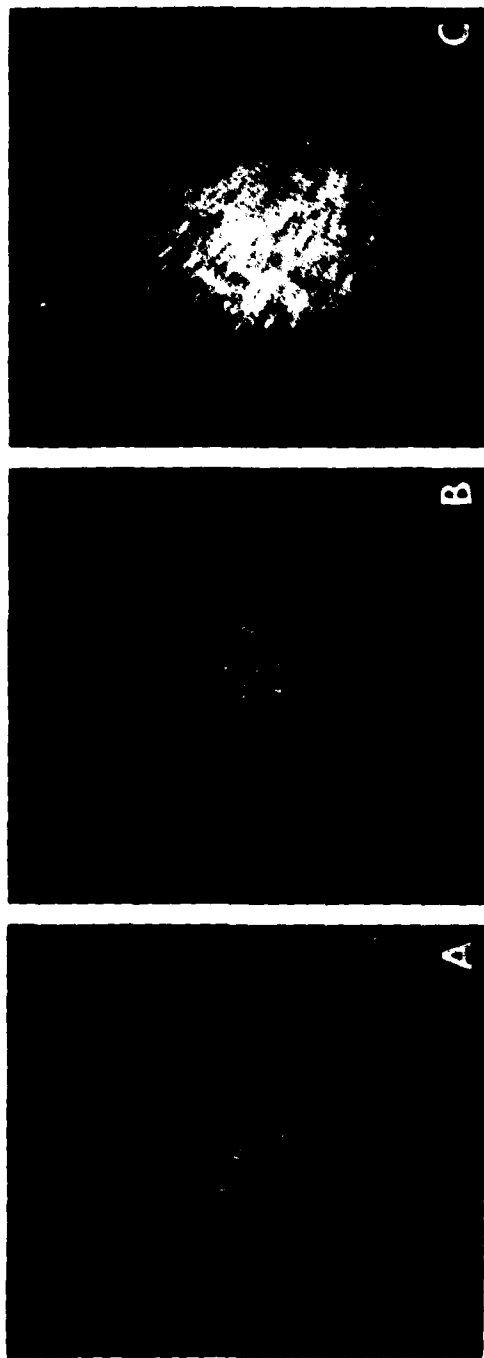
NOTE: Images obtained with the Kitt Peak National Observatory 4 meter telescope. The images are about one arc-second wide, but show that each "speckle" is an actual image. The binary star in 3c has double speckles, and Betelgeuse in 3a has speckles twice as big as the point source star in 3b. Betelgeuse is one of the few stars large enough so that an actual disk rather than a point can be seen.

Figure 3. Short Exposure Speckle Photos for Betelgeuse, Point Source, and Binary Star
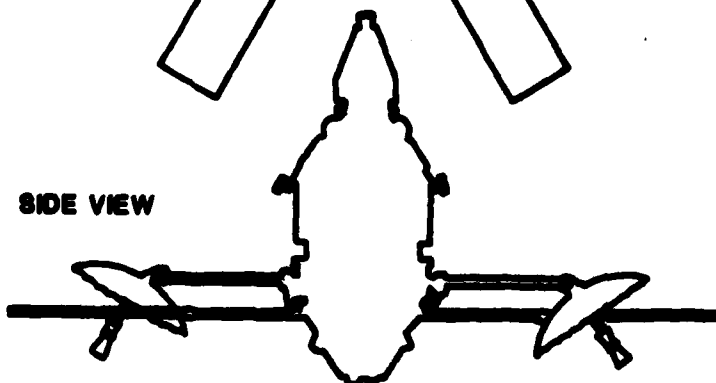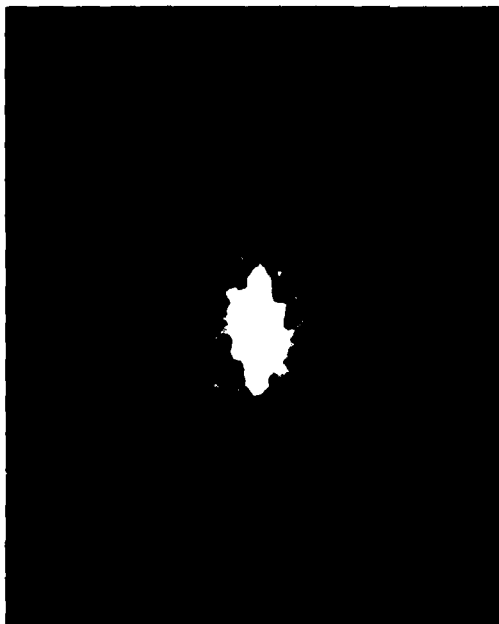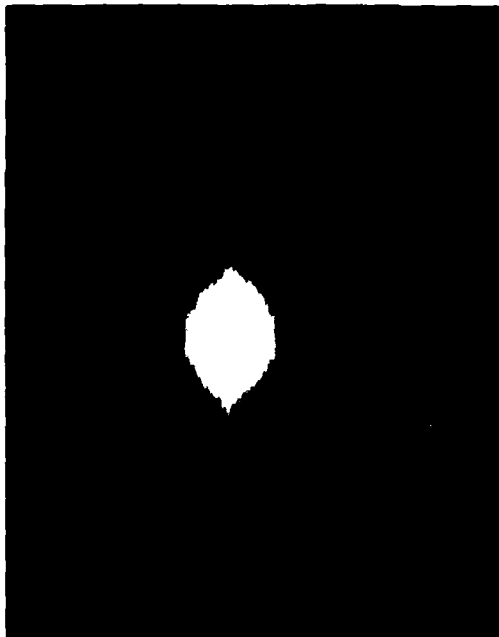
TOP OF SOLAR PANELS

BOTTOM VIEW

SIDE VIEW

0' 1' 2' 3' 4' 5'
6"
SCALE
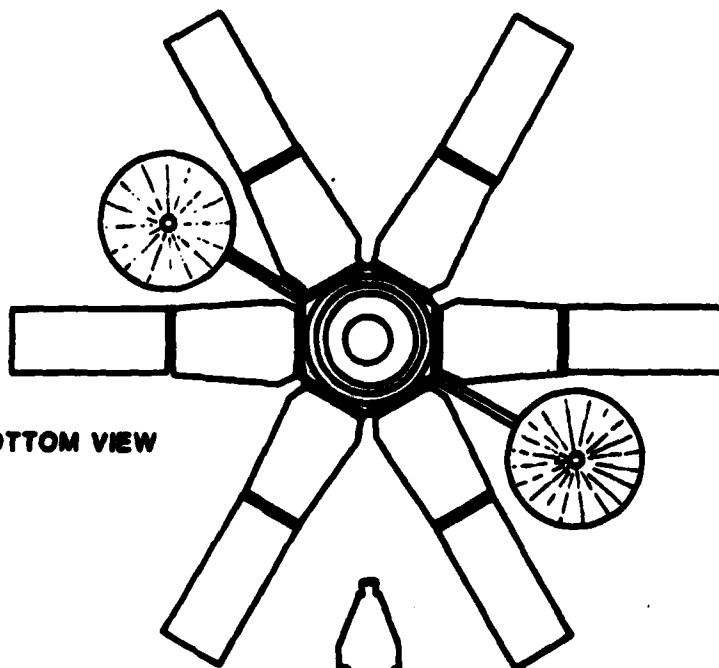
Figure 4. Soviet Communications Satellite Molniya Used as
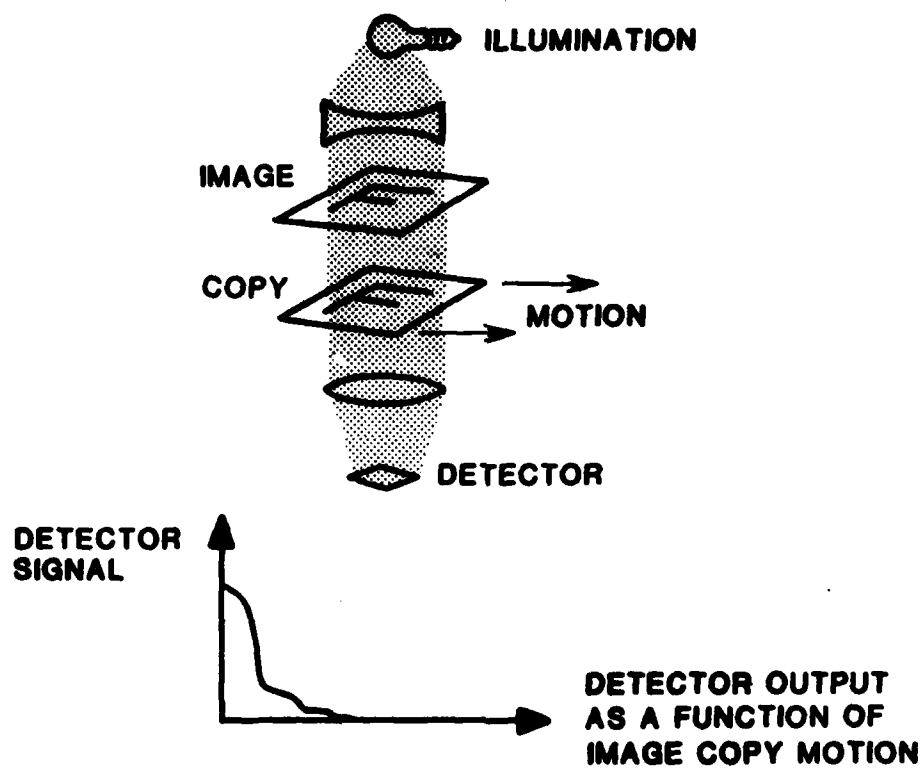Test Target for Speckle Interferometry

18

STELLAR COMPARISON

SATELLITE

0.5 Arc Seconds

0.5 Arc Seconds

NOTE: The oval shape caused by the rotating solar panels is clear in the Molniya results.

Figure 5. Autocorrelations of Point Source Star SAO 30753 and Molniya Satellite at 21,500 km Distance

19

ILLUMINATION

IMAGE

COPY

MOTION

DETECTOR

DETECTOR
SIGNAL

DETECTOR OUTPUT
AS A FUNCTION OF
IMAGE COPY MOTION

NOTE: Before extensive digital processing, autocorrelations were
computed in a manner similar to that shown here.

Figure 6. An Image Autocorrelation
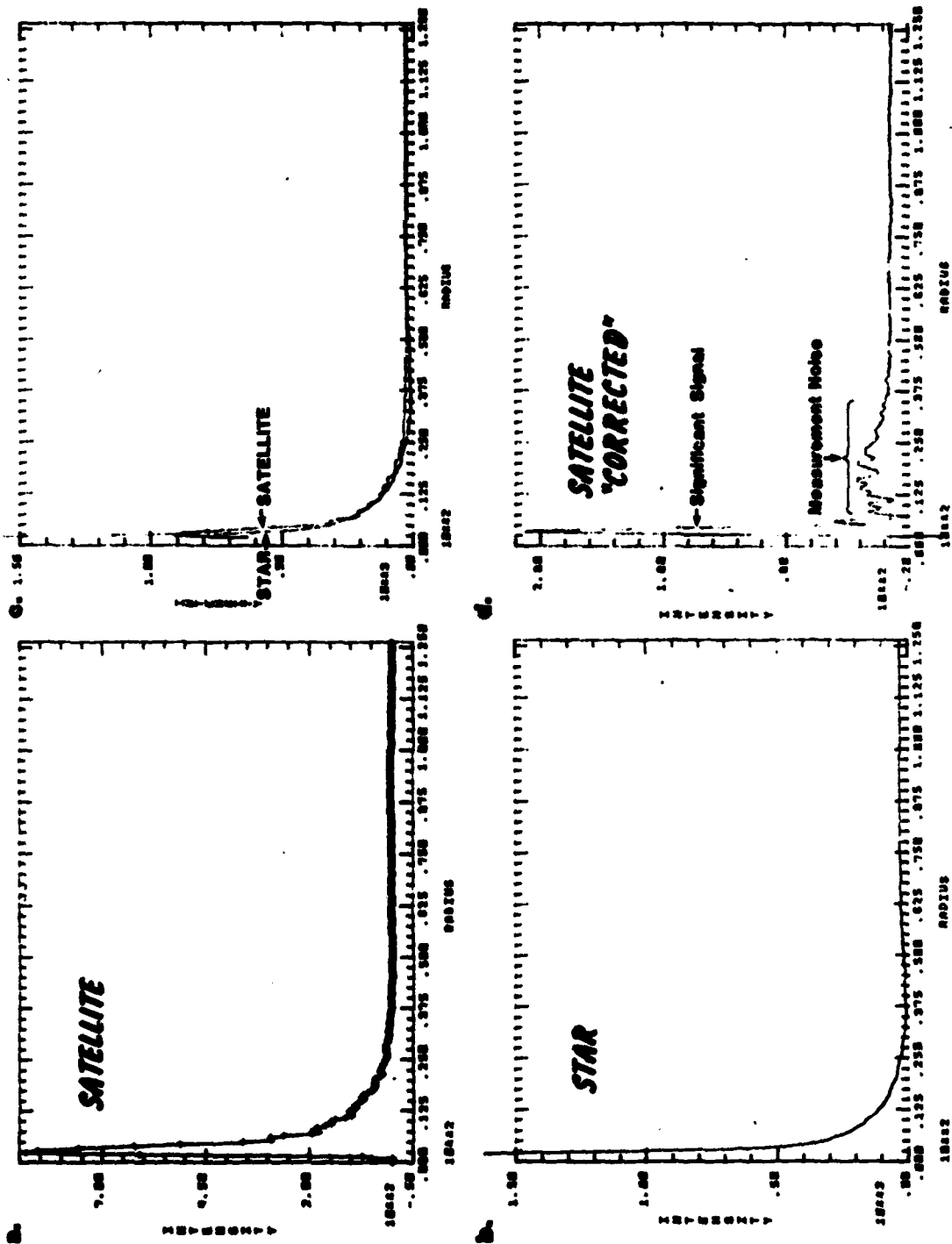
NOTES:

a. The Molniya result.
b. The point source result.
c. a and b superimposed with vertical scales normalized for comparison.
d: The excess autocorrelation a-b from which the Molniya size is computed (vertical scale exaggerated).

Figure 7. Autocorrelation Amplitude vs Radius for Molniya and Point Source Star SAO 30753 (see Fig. 5)

NOTE: This telescope may be used with speckle interferometry to
provide the resolution of a 7 meter telescope.

Figure 8. Multiple Mirror Telescope, Mt. Hopkins, Arizona
(recently completed)

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-83